Parametric Evaluation of Potential Missions for Advanced Propulsion

Presentation to Advanced Space Propulsion Workshop

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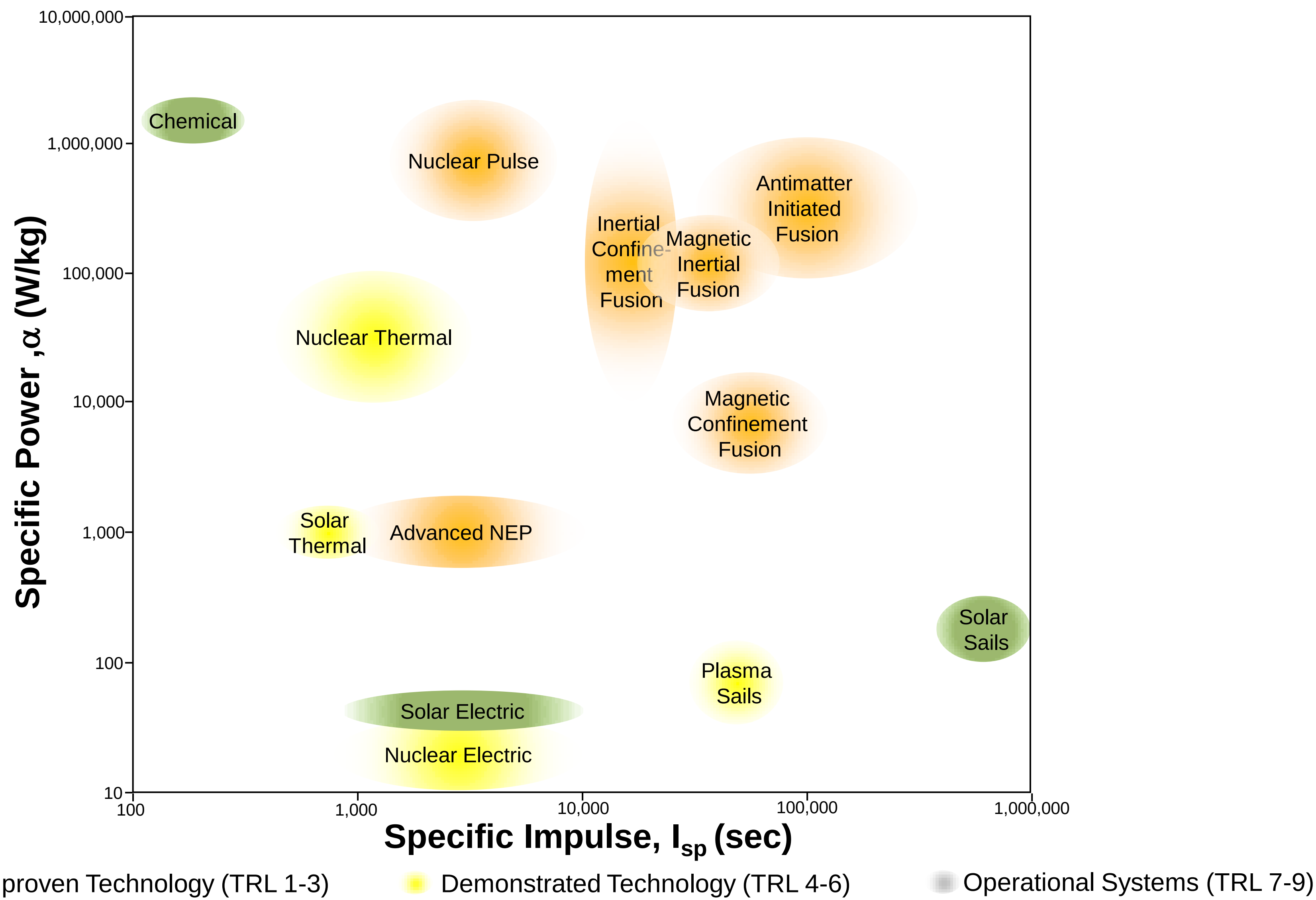
Introduction

- Goals
  - Develop methodology for comparing multiple propulsion concepts for a given mission
  - Evaluation process should be as objective as possible
- Outline
  - Specific Impulse and Specific Power
  - Propulsion Databook
  - Example Results

Propulsion Technologies



Specific Impulse and Specific Power

- Jet power defined as

$$P_{jet} = \frac{1}{2}\dot{m}V_e^2$$

- Thrust defined as

$$F = \dot{m}V_e + \left(p_e - p_a\right)A_e$$

  - Pressure term is small contributor for a well designed nozzle
- Instantaneous specific impulse is

$$I_{sp} = \frac{F}{\dot{m}g_0}$$

- Combining above yields

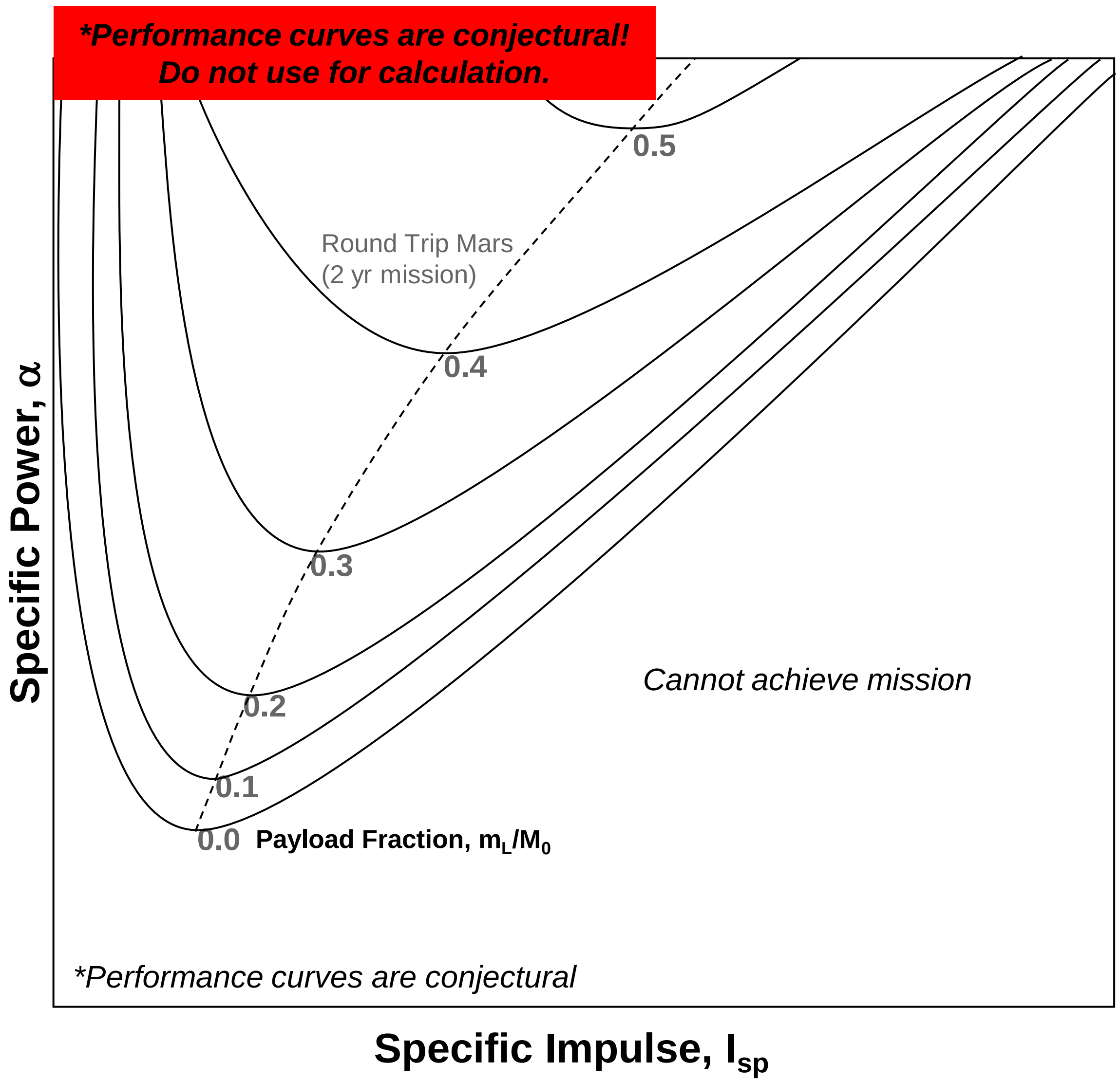
$$P_{jet} = \frac{1}{2}g_o I_{sp} F$$

- Dividing by propulsion system mass yields

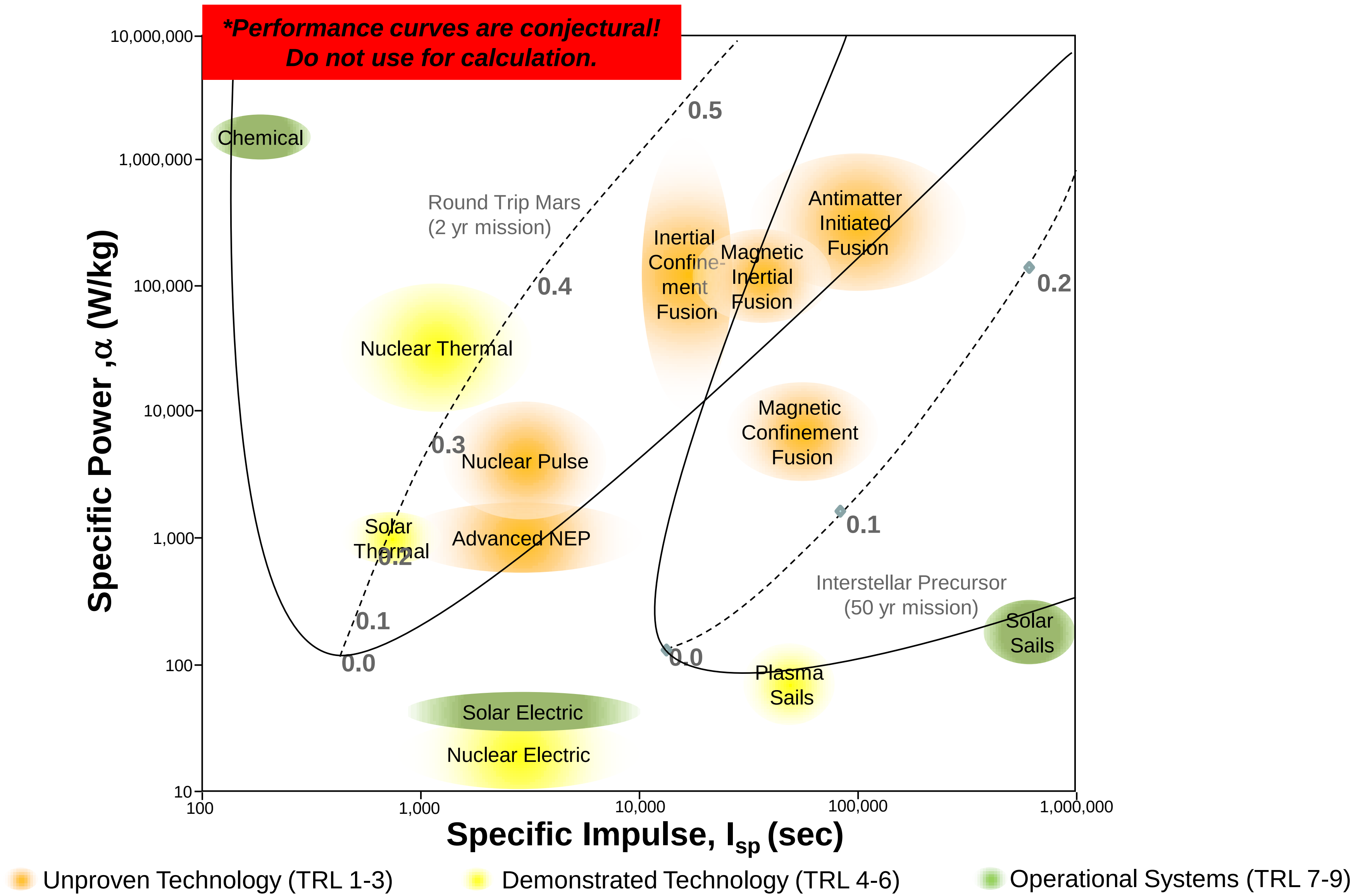
$$\alpha = \frac{P_{jet}}{m_{eng}} = \frac{1}{2}g_o{}^2 I_{sp}\frac{F}{g_0 m_{eng}}$$

  - Defines specific power as function of Isp and thrust-to-weight

Parametric Trajectory Analysis

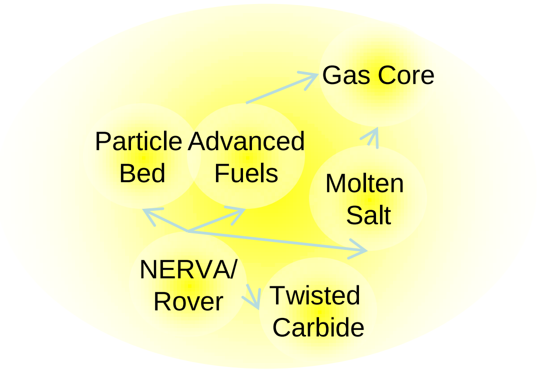


Missions vs. Propulsion Technologies



Propulsion Research Effort

- Each propulsion category can be expanded into individual propulsion concepts
- Nuclear Thermal is expanded here
- Individual concepts are mapped inside bubble with dependencies shown by arrow



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Editing Help
FAQ
User Wishlist

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J-2X PPA-2 Test Program
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Fastrac Overview
J-2X Nozzle Extension
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Toolbox
What links here
Related changes
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Printable version
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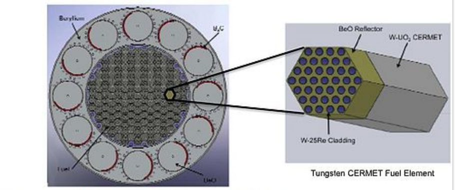
Cermet

Advanced Propulsion Concept Library > Nuclear Concepts > Nuclear Thermal Concepts > Solid Core Concepts > Cermet

Contents [hide]



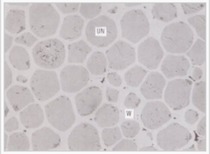
Drawing of a Phoenix CERMET Fission Core with 12 Control Drums and 151 Fuel Elements.

A Cermex Element Illustration

Overview [edit]

Expected Advantages [edit]

Cermet fuels are expected to possess many significant advantages over other nuclear fuel types, including a relatively high burnup(how much energy is extracted from the fuel), the ability to endure many sever thermal transients with out structural failure, a potential for very long operating life, multiple restarts, lighter reactors, and greater compatibility with many propellant types including hydrogen. Cermet Class Nuclear Engines have the expected benefits of a non-cermet nuclear engine including reduced launch mass, shorter trip times due to twice the specific impulse of chemical propulsion thereby increasing mission launch opportunities, but are expected to do so with greater reliability. The expected reliability gain will, potentially, allow for greater Isp, due to being able to operate the engine at higher temperatures, and more engine restarts. Based on previous program developments, fuels with potential for catastrophic failure are not acceptable. This poses a serious challenge for solid block carbon based fuels. Graceful degradation and smaller fuel elements are acceptable options, such as twisted ribbon bunch, particles (mixed carbides), SLHC (CERMET or mixed carbides). However, CERMET fuels may be the only option if complete fission product retention is needed.

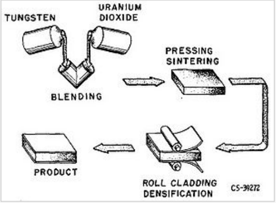

Uranium Nitride in Tungsten

Underlying Theory [edit]

A cermet is a composite made of a ceramic material and a metal. Metals typically posses high strength, ductility, and thermal conductivity, while ceramics have high melting points and are typically chemically resistant. The theory is that a mixture of the two will combine the advantages of both materials. Often the metal particles are given coating that prevent chemical or mechanical deterioration during stress, including thermal, structural or even plastic deformation. A ceramic coating on the metal particles provides the benefit of a ceramic to ceramic interface increasing the structural and chemical properties of the composite material. Since the Isp of a rocket engine is directly a function of the temperature of the gas being expelled through the nozzle, a cermet fuel is a natural choice for consideration as a fuel element in a nuclear rocket engine.

Cermet nuclear fuels are formed by pressing and sintering a mixture of the constituent powders. This is typically done an inerting environment such as hydrogen or a vacuum to avoid oxygen or carbon contamination. Plasma sprays are being investigated as potential manufacturing processes as well.

CERMET fuel development at the NASA Lewis (Glenn) Research Center in the 1960's focused initially on dispersion-type fuel composites with a matrix of tungsten. Tungsten was selected understanding the associated advantages and disadvantages:[4]



NASA Lewis: Fabrication of tungsten - uranium dioxide composites by powder metallurgy techniques [1]

- Advantages:
  - Highest melting point of all the metals, almost 1700F above the selected fuel-element operating temperature.
  - Relatively good strength and excellent thermal conductivity over entire operating range (room temperature conductivity nearly equal to aluminum)
  - Does not react with Hydrogen, the typically chosen NTR propellant
- Disadvantages:
  - Extremely brittle at room temperature
  - At a few hundred degrees, transforms into a ductile state and remains ductile to its melting point
  - Required new manufacturing techniques (potentially overcome today)

Uranium oxide was chosen as the fissionable fuel to go with the tungsten matrix of the dispersion-type fuel elements.

- Advantages:

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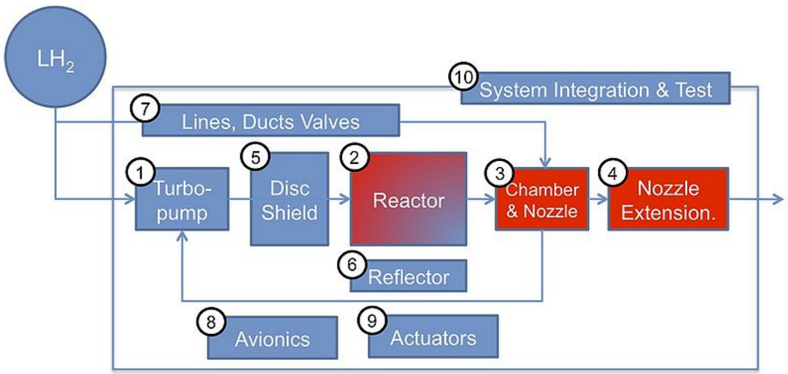


Technology Development Status

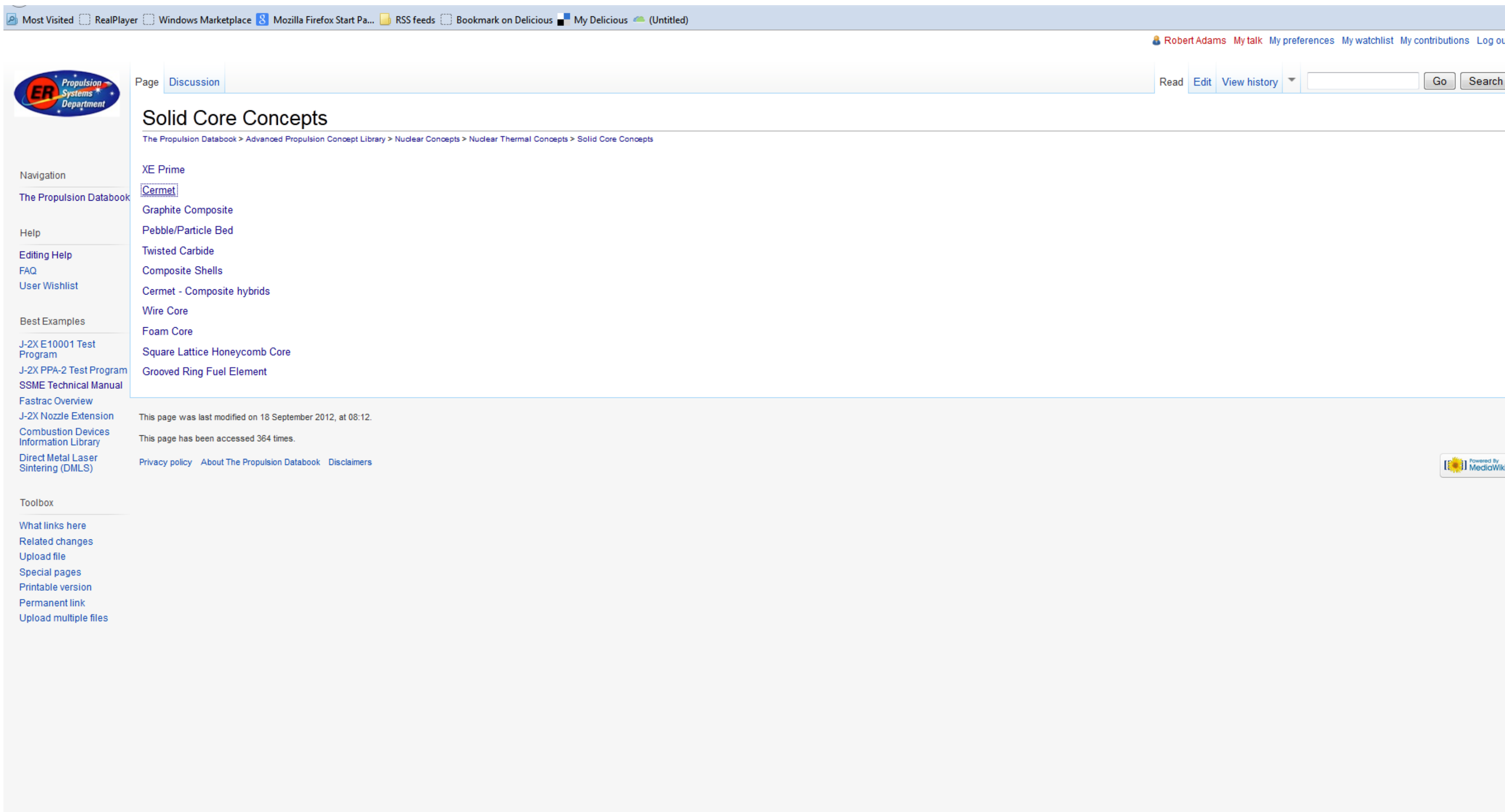
[edit]

Please discuss the status of concept development, proof of principle, or proof of performance activities associated with each component of the Cermet class engine shown above in the engine schematic as they would pertain to this specific application only. Please name the development activity to be statused in the first column. Describe a brief history with pertinent facts in the second column. Please discuss technology issues or gaps in the third column. The issues and gaps listed should capture potential technical risks to a development program. Assume that the issues and gaps captured here will be used to plan technology development activities that would lead to and integrated subsystem testing or engine system level testing. The section below this section is titled Development Planning, this is where the potential technology development efforts will be proposed against the Know Issues given in Column three.

Cermet Class Reactor Technology Status

Reactor Development Activity	Description	Known Issues
General Electric 710 High-Temperature Gas Reactor Program	The GE 710 High-Temperature Gas Reactor Program performed significant analysis, development and testing of cermet fuels to be used in a Brayton cycle space power reactor.	1. Fuels development, configuration, material coatings, burn-up induced swelling and cracking of reactor system components all affect the useful and safe life of a nuclear engine. 2. Fission product retention and water immersion issues.
GE 710 Fuel Failure Mode - Loss of Oxygen from O2	Loss of oxygen from UO2 at high temperatures, formation of sub-stoichiometric UO2, free uranium and penetration of cladding wall with thermal cycling.	Physical Mechanism: Clad transparency (tantalum alloys; T-111) to oxygen at intermediate and high temperatures. Solution Adopted: 1. Changed to tungsten clad material - No oxygen transparency exhibited by this material at any temperature tested. 2. 6% gadolina added to UO2
GE 710 Fuel Failure Mode - Fuel Cracking	Volume expansion and eventually cracking of the fuel matrix (W-UO2) during extremely high temperature operation and after significant thermal cycling.	Physical Mechanism: Coefficient of thermal expansion (CTE) mismatch; UO2 and tungsten in fuel matrix. Thermal cycling at high temp. causes fuel particles to pull apart from the tungsten matrix. Solution Adopted: Alloy tungsten with Re, Mo-Re. Change to UN for lower CTE mismatch.
GE 710 Fuel Failure Mode - Fission Product	Fission product damage/release after 4000/7500 hours of operation at 1870-2270 K in selected fuel specimens	Physical Mechanism: Fission product damage to the cermet/clad (small surface blister) caused by accumulated buildup of pressure, lattice stresses, and dislocation weaknesses inherent in fuel materials under irradiation.

Propulsion Databook



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Navigation
- The Propulsion Databook

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- Editing Help
- FAQ
- User Wishlist

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- J-2X E10001 Test Program
- J-2X PPA-2 Test Program
- SSME Technical Manual
- Fastrac Overview
- J-2X Nozzle Extension
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- What links here
- Related changes
- Upload file
- Special pages
- Printable version
- Permanent link
- Upload multiple files

- XE Prime
- Cermet
- Graphite Composite
- Pebble/Particle Bed
- Twisted Carbide
- Composite Shells
- Cermet - Composite hybrids
- Wire Core
- Foam Core
- Square Lattice Honeycomb Core
- Grooved Ring Fuel Element

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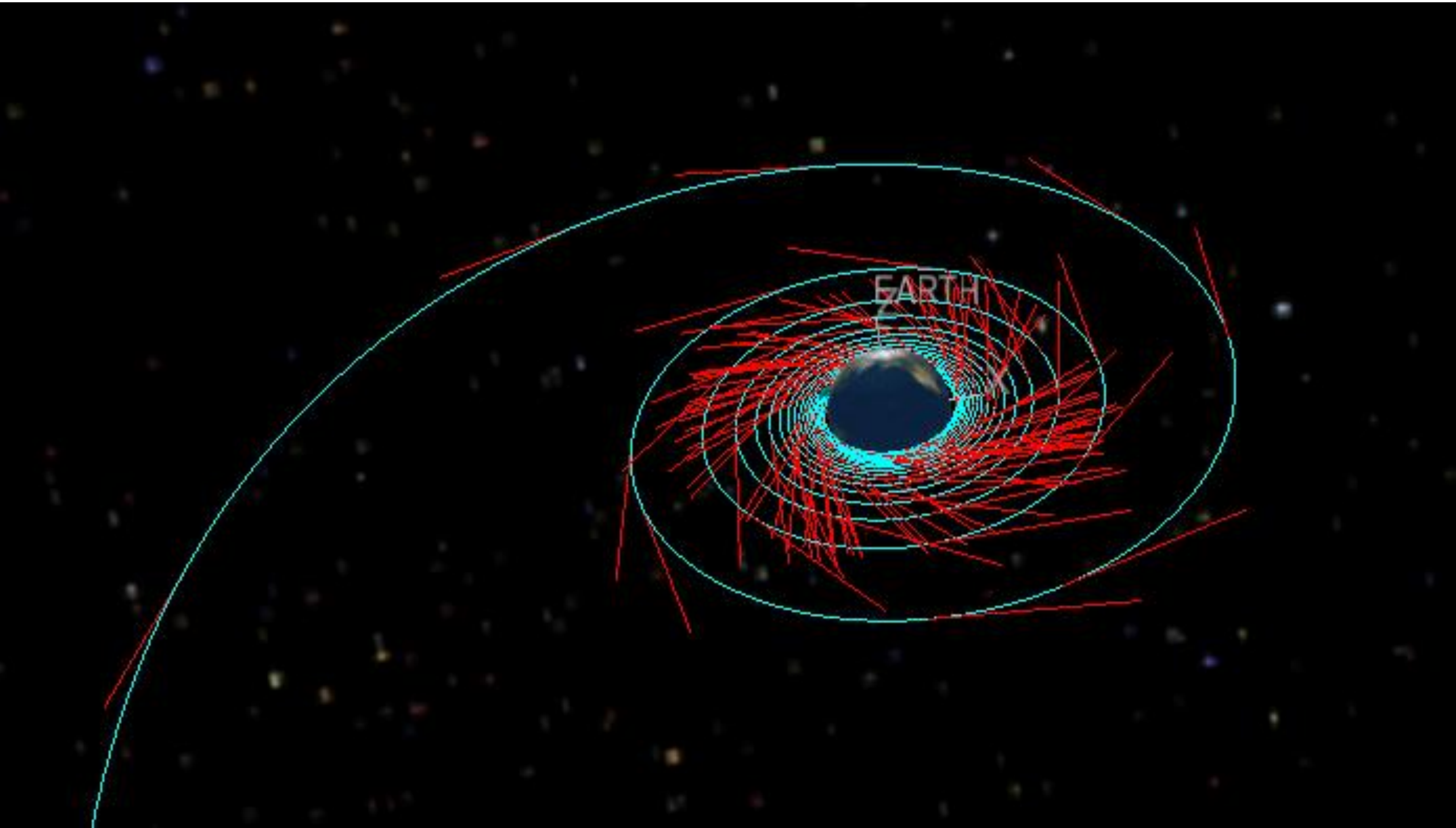
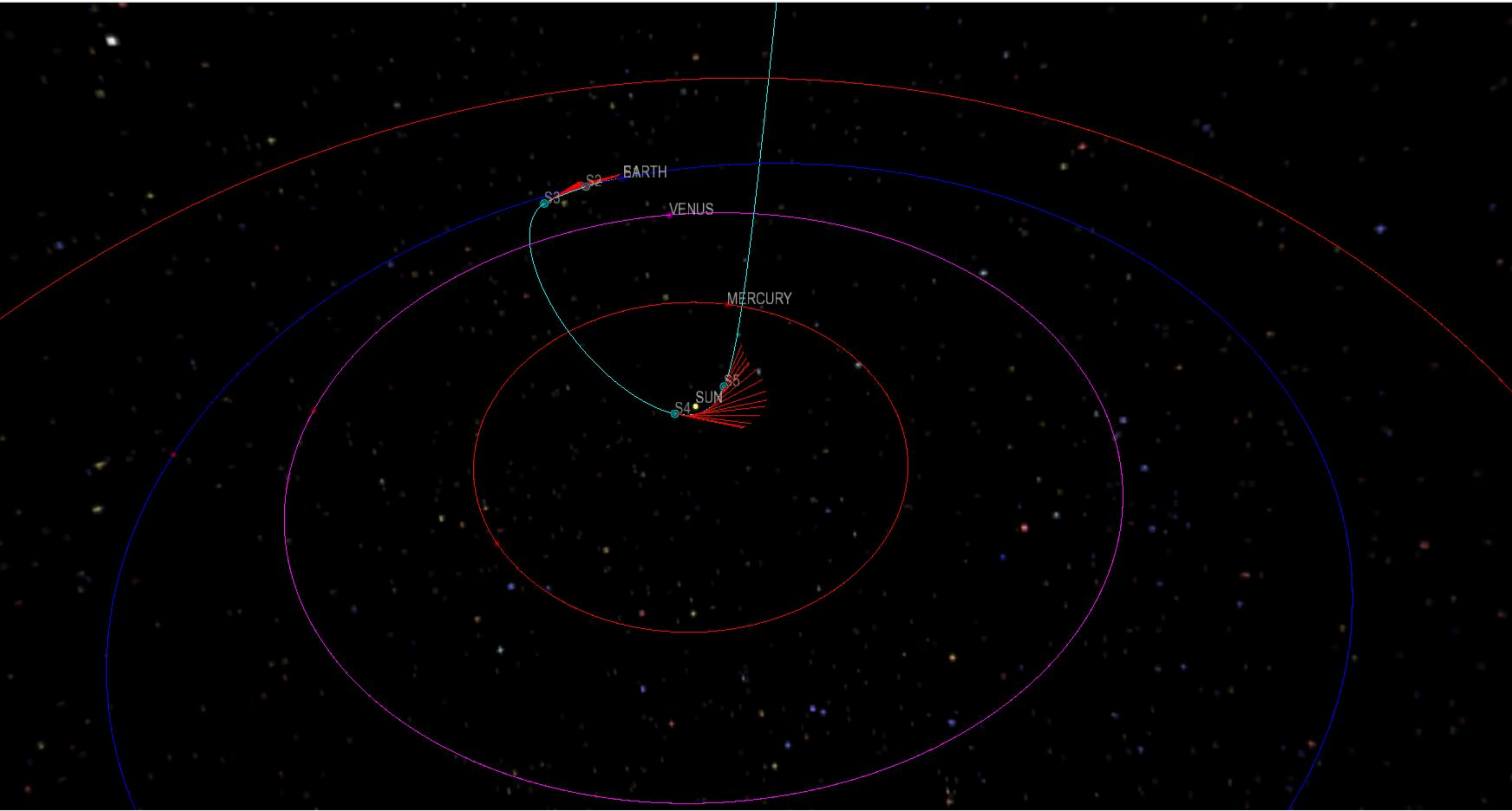
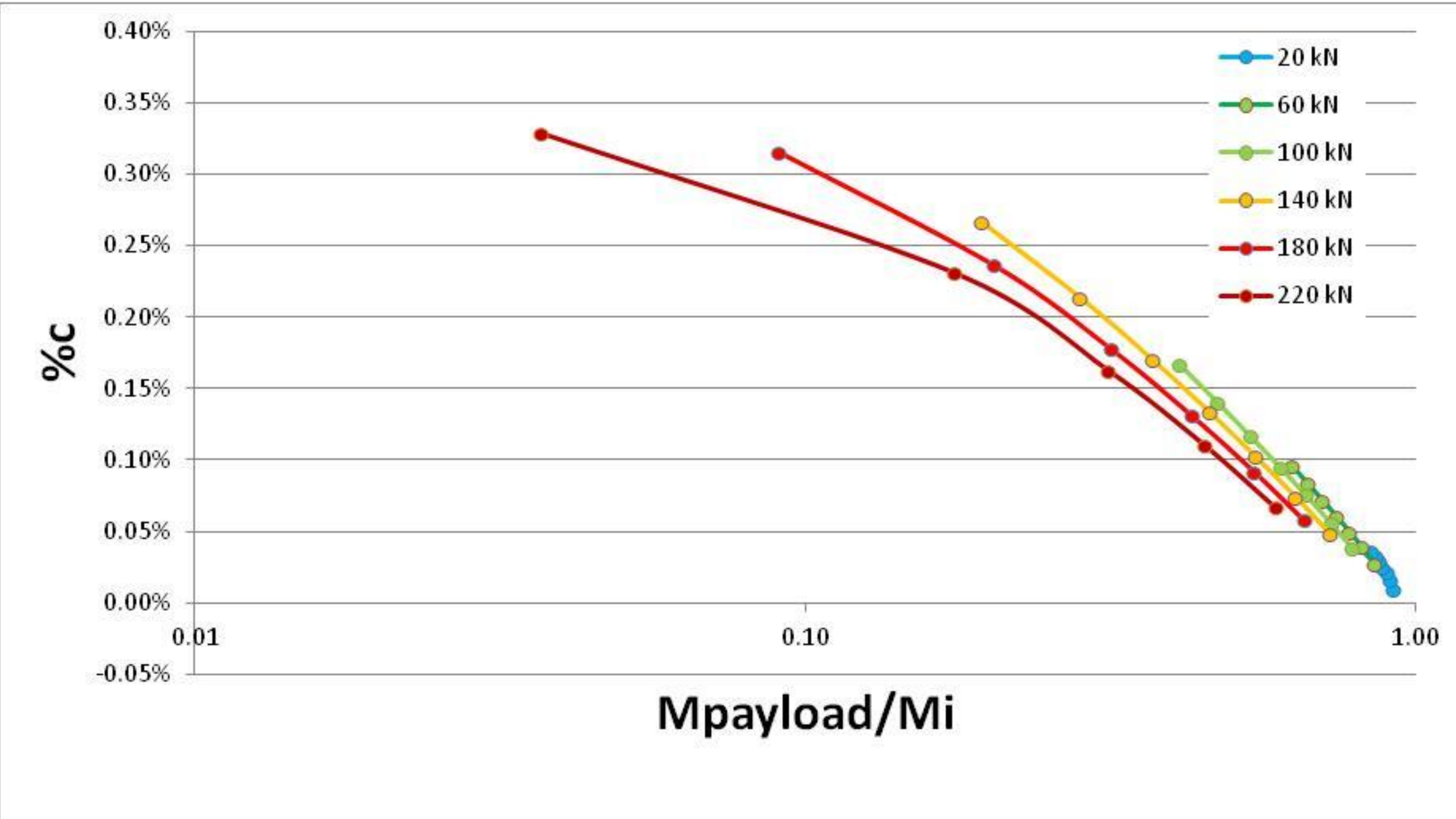
Earth Escape



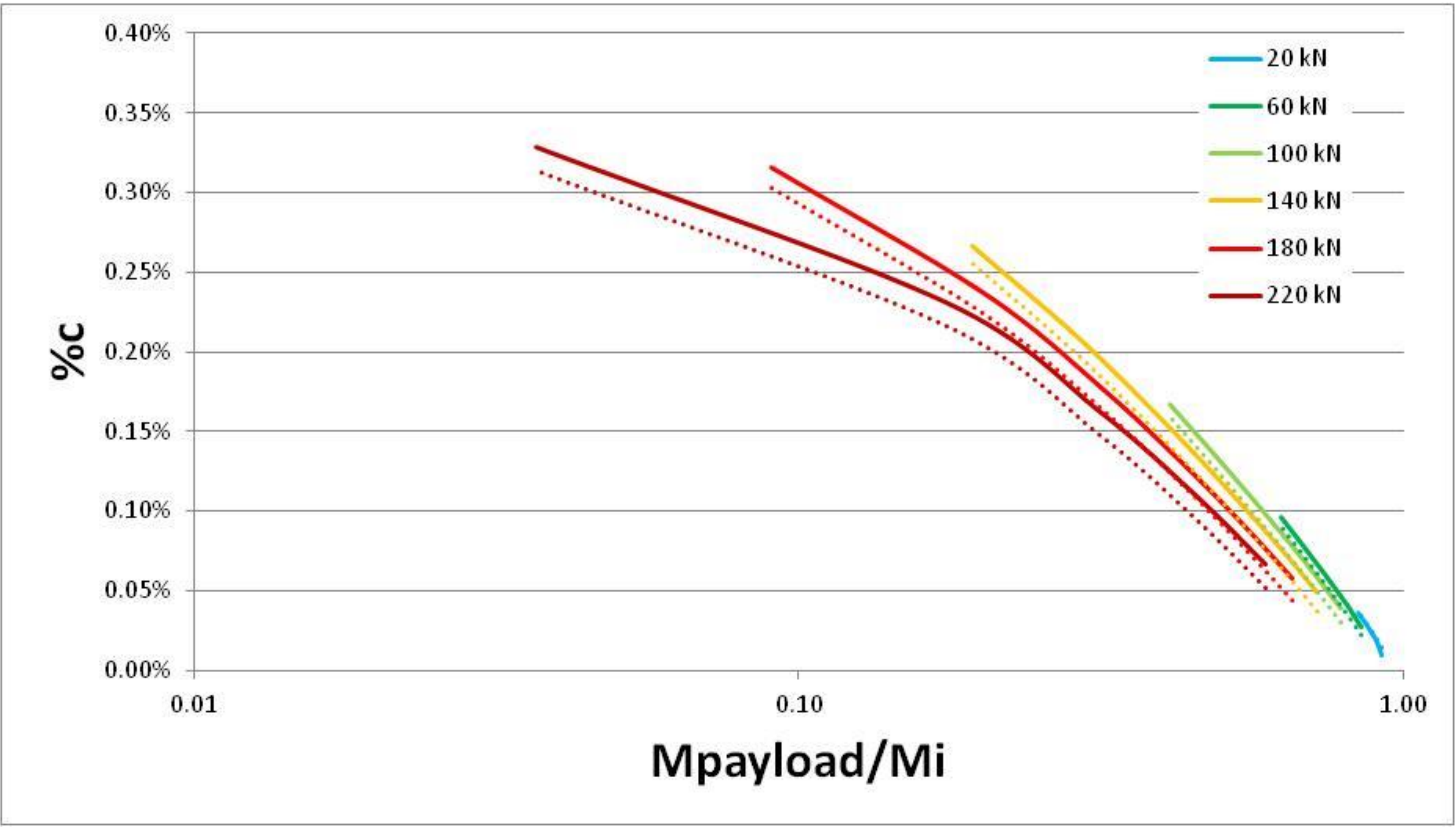
Solar Escape



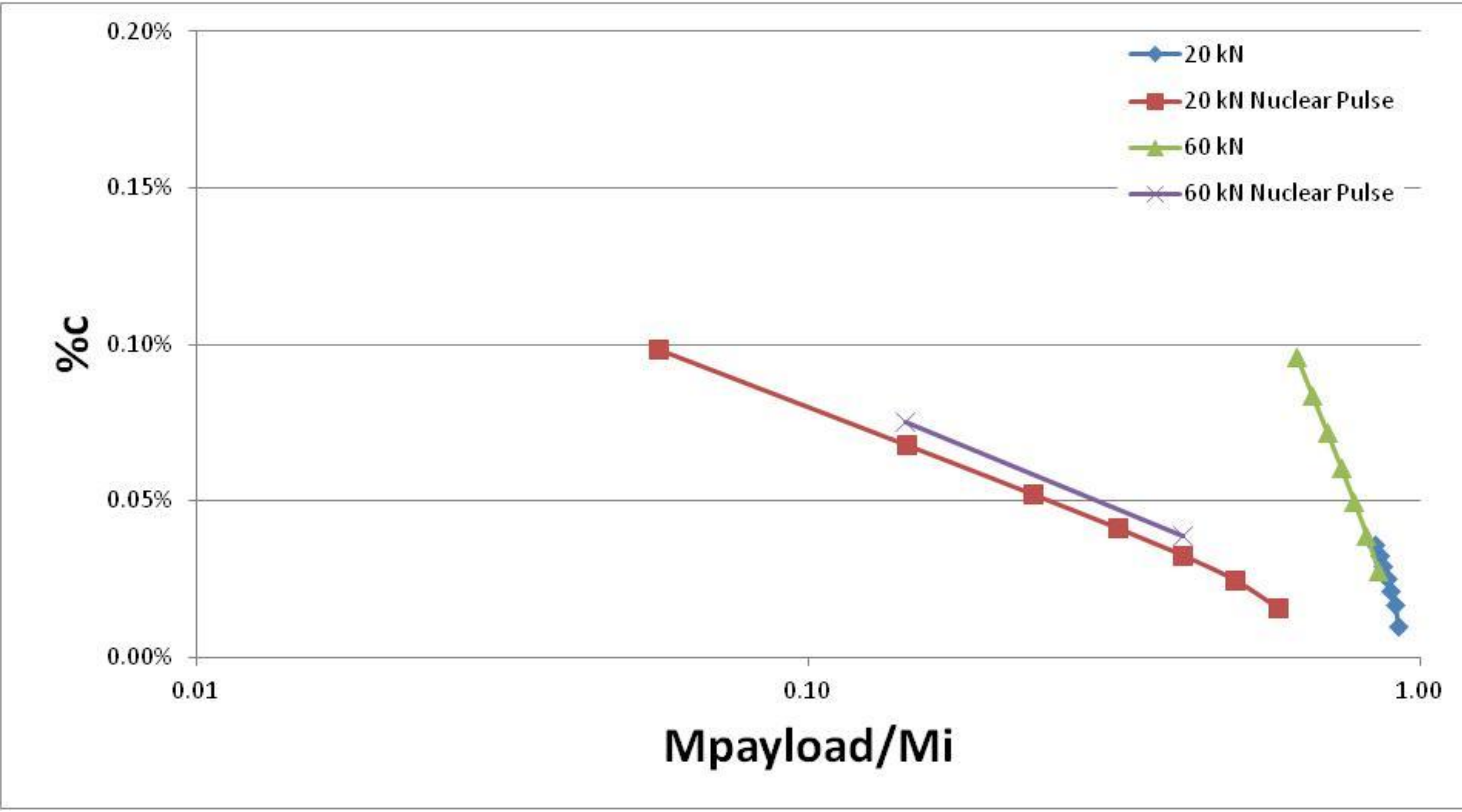
PJMIF Performance



PJMIF Performance vs. Ideal



PJMIF Performance vs. Nuclear Pulse



Conclusions

- Propulsion Databook needs contributors
  - Issues with providing access, ITAR requirements
- Missions vs. Propulsion technologies gives single chart view of comparable performance
  - Requires substantial effort to create trajectory contour plots
  - Work is ongoing

Acknowledgements

- NASA – MSFC for supporting my efforts with Project Icarus
- G. Richardson for co-authoring previous work in exploring the Oberth maneuver